

CONTRACTOR REPORT

SAND87-7012
Unlimited Release
UC-60

C.1

65846 8024



A Design Code to Study Vertical-Axis Wind Turbine Control Strategies

William A. Vachon
W. A. Vachon & Associates, Inc.
Manchester, MA 01944

Prepared by Sandia National Laboratories Albuquerque, New Mexico 87185
and Livermore, California 94550 for the United States Department of Energy
under Contract DE-AC04-76DP00789

Printed July 1987

1081370

Issued by Sandia National Laboratories, operated for the United States Department of Energy by Sandia Corporation.

NOTICE: This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of *their* employees, nor any of *their* contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government, any agency thereof or any of their contractors or subcontractors. The views and opinions expressed herein do not necessarily state or reflect those of the United States Government, any agency thereof or any of their contractors or subcontractors.

Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

NTIS price codes
Printed copy: A03
Microfiche copy: A01

SAND 87-7012
Unlimited Release
Printed July 1987

Distribution
Category UC-60

A Design Code to Study Vertical-Axis

Wind Turbine Control Strategies

William A. Vachon
W. A. Vachon & Associates, Inc.
Manchester, MA 01944

Sandia Contract No. 21-8481

ABSTRACT

A computer code called ASYM is described. The code permits a wind turbine designer to examine the role of low and high wind speed cut-in and cutout control strategies on the production of energy and the consumption of fatigue life by a wind turbine. The primary goal of the code development has been to create a design tool to optimize the energy production and the fatigue life of a wind machine through optimized high wind speed control schemes. The code is also very useful in evaluating start-up algorithms. It works primarily in the time domain and simulates high-frequency random wind of specific statistical characteristics while employing energy and damage density functions to calculate the results. A modified net present value calculation of the annual machine revenues and costs over the calculated life of the wind turbine is used to compare the merits of various control algorithms. Typical results are provided to demonstrate the use of the code.

ACKNOWLEDGEMENT

This effort has been sponsored by the Wind Energy Research Division at the Sandia National Laboratories under funding from the U.S. Department of Energy.

1. INTRODUCTION

Obtaining long-term economic performance from a wind turbine depends on the following considerations:

- (1) Initial machine cost,
- (2) Installation at a good wind site,
- (3) Low operation and maintenance costs,
- (4) High electric energy production, and
- (5) Acceptably long life before machine wear out due to material fatigue.

The first three concerns are largely dictated by the pricing policy of the manufacturer and/or vendor, the selection of the site, and details of the machine design. The last two considerations can, however, be very much affected by the manner in which the machine is controlled during start-up, operation, and shut-down. For example, if a wind turbine is operated all of the time, even in high winds, a great deal of energy may be generated but the machine may fail prematurely due to stress-induced material fatigue.

This paper describes a theoretical computer model that has been under development by the Sandia National Laboratories (SNL) for several years. The code, with the acronym ASYM, simulates a second-to-second random wind with prescribed properties (i.e., annual average wind speed, probability distribution, turbulence etc.). The random wind is then input to a simulated wind turbine with specific control algorithms, as well as specific material fatigue and output power characteristics. The model can be used to simulate and select optimal values for wind turbine start and stop control decisions based on wind speed (both high and low), power, energy, or fatigue damage rate. The model also permits an evaluation of the merits of rotor motoring and/or coasting conditions. Various other important considerations such as wait times and averaging times are also employed in the control algorithms. The results facilitate the selection of the optimum control parameters to maximize the wind turbine's life cycle cost (LCC), net present value (NPV), or other economic figure of merit over a preselected timeframe (eg., useful life for tax purposes) or the machine fatigue life.

Background

Researchers at the Battelle Pacific Northwest Laboratories (PNL) modeled the control algorithms of horizontal-axis wind turbines (HAWTs) as a means of studying the sensitivity of energy production to different control approaches and to different wind characteristics [1]. Machine fatigue damage was not a part of the model. The model compared machine energy production predictions based on control strategies using 2-minute wind speed averages compared to hourly averages. Due to an extreme paucity of higher frequency wind data, the 2-minute averages from several Department of Energy (DOE) wind stations were the best real wind data base available for such an evaluation. The analytical comparison found that, depending on

the site's wind characteristics, deviations in energy production predictions of up to 50 percent could arise.

The development of vertical-axis wind turbine (VAWT) technology within the United States' wind program has been the responsibility of SNL. Potential VAWT rotor fatigue damage due to vibratory stresses and its relationship to machine control algorithms have been under study for several years at SNL. The effort has resulted in a useful analytical procedure for damage prediction based on a damage distribution that is developed as a function of wind speed [2,3]. The method provides the basis of the fatigue portion of the code discussed in this report.

Similar to the Battelle work, SNL conducted studies to optimize VAWT cut-in control strategies. The analytical studies relied on measured wind speed data derived from a DOE wind station in Bushland, Texas. These efforts resulted in the development of a code called AUTOSIM. It simulated supervisory control algorithms pertaining to low wind speed averaging times as well as average wind speed and/or power levels that must be achieved for machine start-up. The studies were aimed at maximizing the wind turbine "on time" that is directly related to energy production [4,5]. Recognizing the shortage of measured high-frequency wind data by which to study high wind speed cutout phenomena, SNL then embarked on the theoretical development of a high-frequency random wind generator. The mathematical approach has been described in the literature [6] and forms the basis for the random wind simulator that is employed in the code ASYM.

2. CUMULATIVE FATIGUE DAMAGE

VAWTs exhibit a characteristic rotor vibratory stress, the root mean square (RMS) level of which increases monotonically with wind speed as shown in Figure 1. This characteristic results from the fact that (1) with each rotor revolution a blade passes through the machine's wake, and (2) the lift on the blade changes direction twice with each rotor revolution. As a result, VAWTs are usually shut down at higher wind speeds [approx. 20 m/s (45 mph)] to reduce rotor fatigue stresses.

The economic rationale for restricting VAWT operation at high wind speeds has been that (1) there are very few hours when the wind blows above these levels, therefore little energy is lost; (2) extreme rotor fatigue damage can begin to occur during high wind speed operation, leading to a dramatic reduction in machine life; and (3) because current VAWTs continue to increase their power output at high wind speeds, associated higher torques will also dictate a stronger and more costly machine drive train to accommodate higher wind speed operation.

To evaluate the effects of cutout wind speed on VAWT energy production and machine life, fatigue damage density and energy density functions are used. The former is the distribution of the fatigue damage as a function of wind speed, whereas the latter is the distribution of wind energy potentially available from the wind turbine at each wind speed. Figure 2 is a plot of the energy and damage density functions (EDF and DDF respectively) for a typical VAWT. The energy density function represents the fractional amount of energy that can be generated at each wind speed based on the wind spectrum and the machine's power curve. The damage density function is the amount of fatigue damage at the most highly stressed joint (usually in the rotor of a VAWT) at each wind speed and is calculated according to Veers [3]. The total energy produced and the total fatigue damage that could occur to a machine if it ran all the time are represented by the total areas under the curves in Figure 2. In reality total damage is the damage rate at each wind speed multiplied by the fractional "on time" at that wind speed. Energy production is viewed in a similar manner. The total fatigue damage is the inverse of the expected machine life.

In Figure 2 it can be seen that if the wind turbine is not permitted to operate above 18 m/s (40 mph) little energy will be lost, but nearly half of the fatigue damage will be saved. Because ASYM calculates both energy production and fatigue damage simultaneously, it provides a method of (1) selecting the optimum cutout wind speed and (2) controlling the machine to maximize revenue to the wind project over the life of the machine.

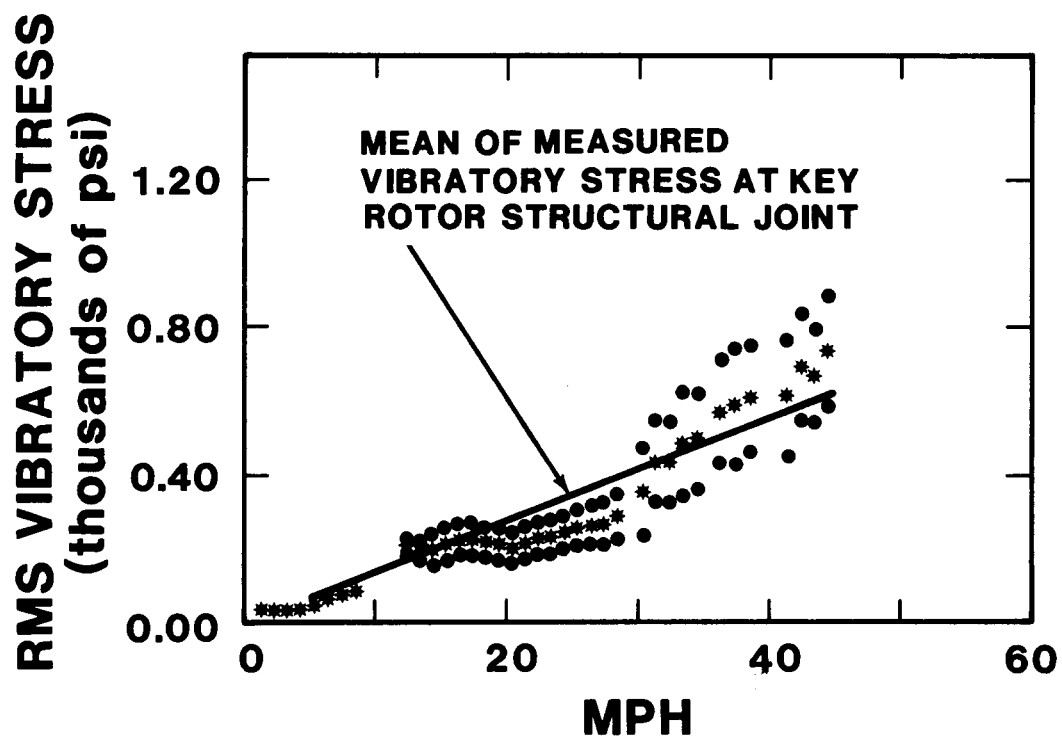


Figure 1. Typical VAWT RMS Vibratory Stress Vs. Wind Speed at Most Highly Stressed Rotor Joint

TYPICAL ENERGY AND DAMAGE DENSITY FUNCTIONS

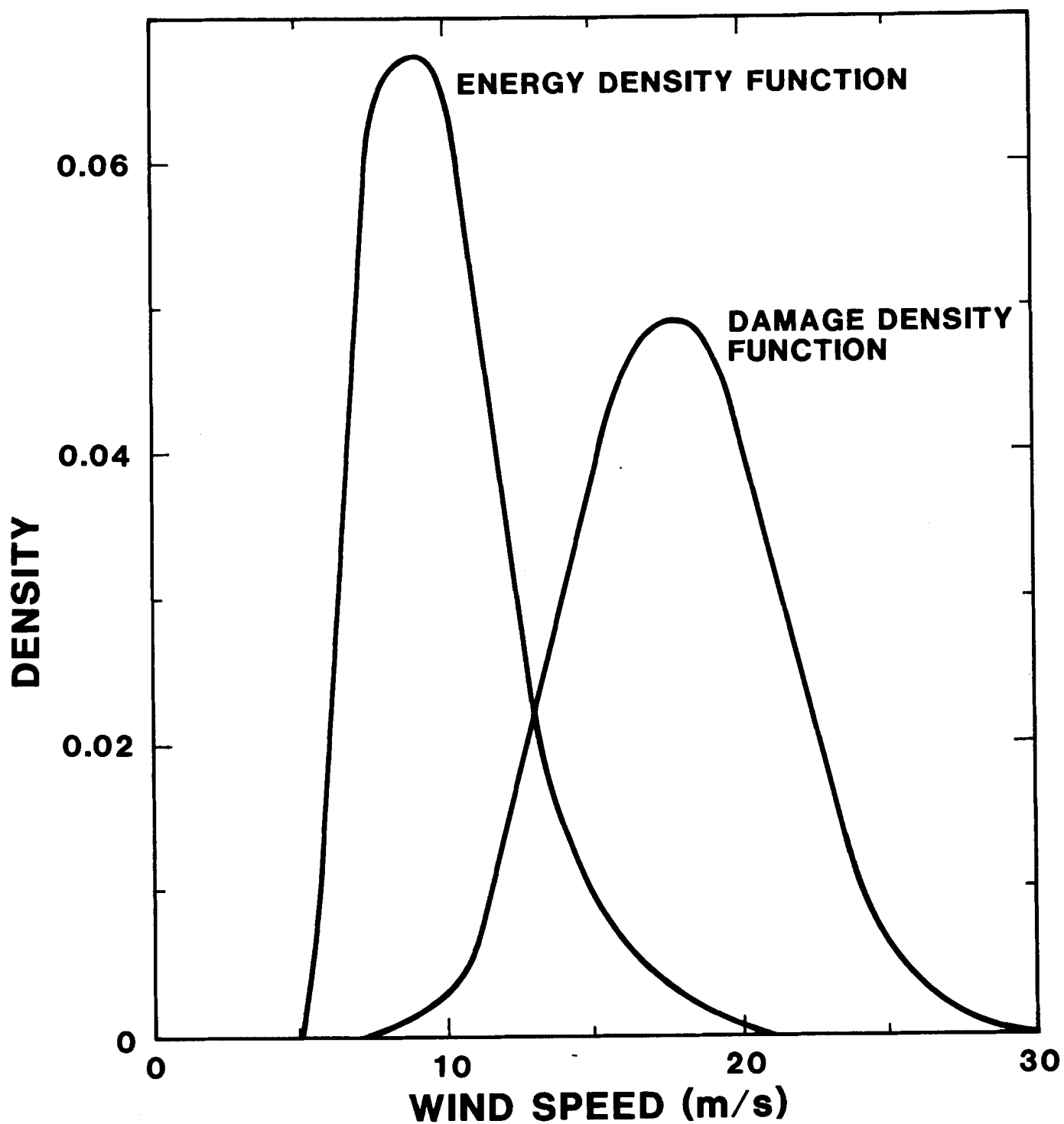


Figure 2. Typical Energy Density (EDF) and Damage Density (DDF) Functions

3. COMPUTER CODE DESCRIPTION

Figure 3 is a block diagram of the ASYM model that is currently written in Fortran 77 code and is operational on an IBM-compatible PC. The overall model is controlled by the main program that sequentially calls subroutines for each of the functions shown. Most of the important control and fatigue-related variables are directly input at the beginning of a run. A few of the more important elements of the model are briefly discussed below.

Random Wind Generator

As discussed in McNerney & Veers [6], a second-by-second random wind is generated in two steps. First, the hourly average values are computed in a random manner, guided by the requirements of a Rayleigh distribution and a pre-defined long-term mean wind speed. The value at each hour is determined by a Markov random walk process with a prescribed autocorrelation decay. During each hour the turbulence spectrum is determined according to the Frost, Long, and Turner turbulence spectrum [7] that is inverted by a fast Fourier transform to provide a time series. The resultant stream of high-frequency wind data is then normalized to conform to a specific hourly average, and subsequently randomized.

Fatigue Model

As ASYM calculates various timing and energy parameters during control algorithm simulation, it also calculates fatigue damage at the most highly stressed structural joint. The fatigue damage model used in past Sandia work [8] employs Miner's cumulative damage rule to predict the damage at each stress level, S , based on the number of stress cycles, n , at each level. Miner's rule relies on the S - n curve at failure for a material or joint being stressed. Appropriate "knock down" factors (for stress concentration, etc.) are assumed in order to account for differences in stress between those of a laboratory test piece and those of an operational VAWT.

The RMS stress level is approximated by the wind-stress function shown in Figure 1 and the number of cycles at each stress level is determined from the predominant cycle rate of the machine. For VAWTs, the average cycle rate can be estimated by taking the ratio of the second moment to the zero moment of the stress-frequency spectrum [3]. It can, however, be approximated by the two-per-revolution excitation frequency that is dominant in the case of a VAWT rotor with two blades. A more recent SNL report provides a more comprehensive summary of the fatigue module within the ASYM code [9].

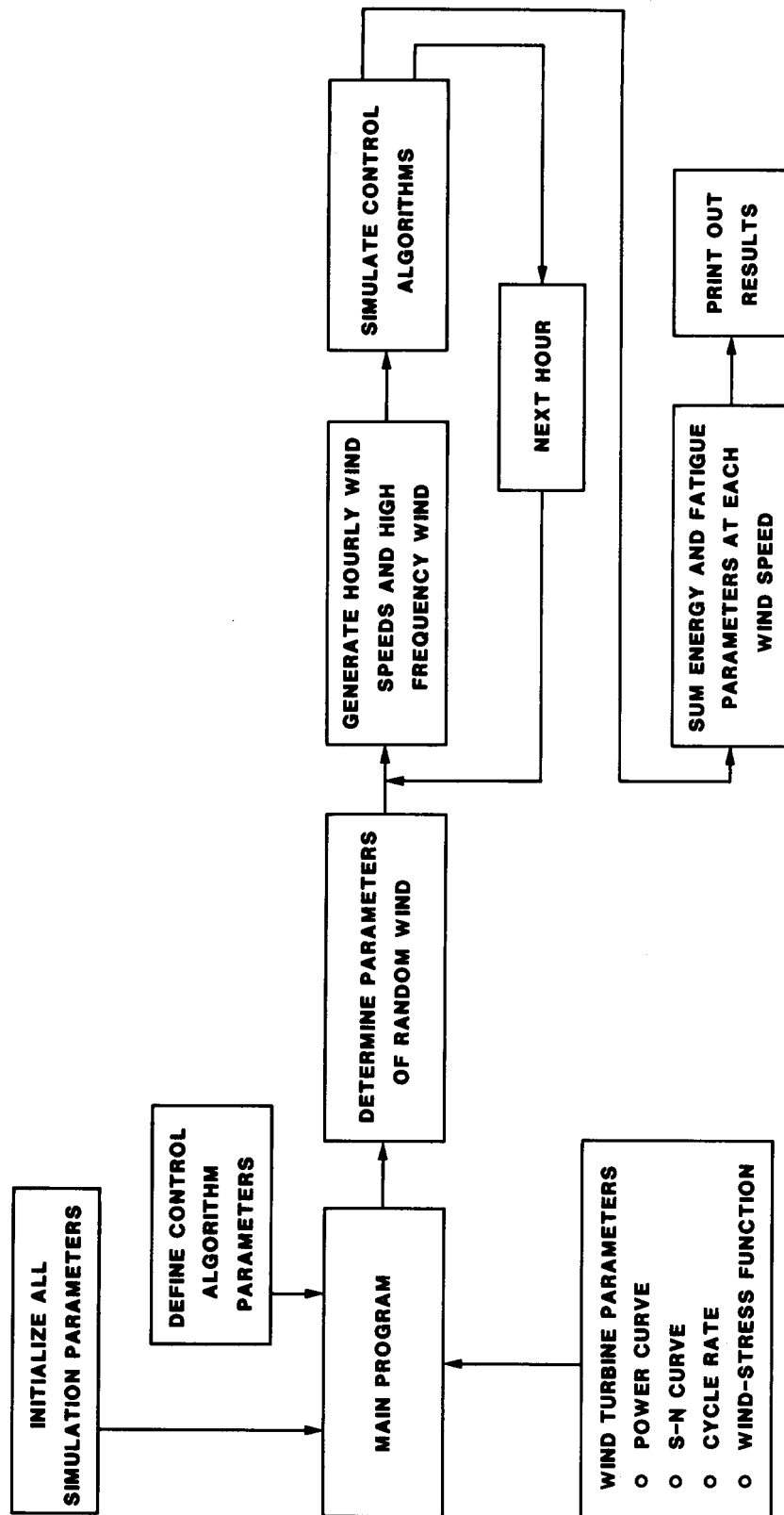


Figure 3. Block Diagram of ASYM Simulation Code

Control Algorithms

Several types of wind turbine control algorithms have been modeled with ASYM. Additional options could also be evaluated with minor modifications. Definitive low wind speed analyses have been previously carried out using AUTOSIM [5], but ASYM could be applied for the same purpose. The main emphasis and the unique value of ASYM is that it permits an evaluation of various control choices at high wind speeds. Some of both the low and high wind speed control schemes are briefly described below.

Low Wind Speed Control Algorithms. There are roughly six low wind speed control options available. The main objective of the strategy is to minimize machine starts and stops and motoring losses, while maximizing "on time" or energy production. The approaches include start and stop decisions based on:

- (1) A discrete wind speed average in which action is initiated when a single wind speed value exceeds a specific level,
- (2) A moving wind speed average (or window) where action is initiated based on the average of a fixed number of wind speed values - the latest value included and the oldest value in the moving window eliminated at each step,
- (3) A discrete power average,
- (4) A moving power average,
- (5) A discrete double power average where wind speed values are analytically converted to an appropriate VAWT power output, based on the power curve. Action is effected based on either a low threshold value of average power computed over several sampling intervals, or a higher value computed over fewer samples, and
- (6) A "Canadian coast" algorithm in which the generator motors when unloaded for winds below cut-in speed.

The single moving power average algorithm has been recommended in a past SNL report as the most efficient approach [4].

High Wind Speed Control Algorithms. There are also several high wind speed control algorithms that may be used. The main objective of a cutout algorithm is to protect the wind turbine from either catastrophic failure or long-term fatigue damage. In a manner similar to that described for low wind speed control, high wind speed control schemes include machine cutout based on:

- (1) A discrete wind speed average,
- (2) A single moving wind speed average,
- (3) A double moving wind speed average,

- (4) A moving power average, or
- (5) An excessive damage density rate.

In addition, each cutout condition will have an associated wait time following cutout, and a high wind speed cut-in condition that may have a threshold at a lower level than the cutout threshold.

Financial Figure of Merit

In its present form ASYM computes the financial merits of a project by calculating a subset of the net present value of the annual cash flows over the useful life of the machine. The machine's lifetime is based on its estimated fatigue life calculated by ASYM. Estimates of the annual percent energy capture are also calculated by ASYM. The simplified net present value is shown in the following equation in terms of key economic parameters.

$$NPV = EA[\% \text{ (Energy Capture - O\&M)}] \left[\sum_{i=0}^N \left(\frac{1}{1+D} \right)^i \right],$$

$$(\text{Energy Cost}) - (\text{Machine Cost}) \quad (1)$$

where EA is the annual energy available, N is the expected machine life (years), and D is assumed to be the discount rate or prevailing inflation rate. The economic figure of merit (FOM) is assumed to be given by the function within the brackets and is given by Equation (2). It represents a simplified function whose value might be affected by the manner in which the machine is controlled. The FOM will be used as a standard of comparison for simulation results to be discussed later.

$$FOM = [\% \text{ (Energy Capture - O\&M)}] \left[\sum_{i=0}^N \left(\frac{1}{1+D} \right)^i \right]. \quad (2)$$

4. TYPICAL RESULTS

During wind turbine operation, the control system is assumed to sample wind speed or power periodically and to send the measurement to the controller. For the model results to be discussed, the sampling period is every 2 seconds. This parameter can be varied. The information is used to calculate either a discrete or a moving average and to compare the value to a threshold level that has been established in the controller. If a threshold is exceeded, either instantaneously or as an average (as dictated by the algorithm), machine control will be affected.

To provide insight into useful applications for the model and to illustrate its value, a few examples of model results are presented. For these examples, a Rayleigh-distributed wind spectrum with an average speed of 8 m/s (17.9 mph) and a surface roughness length scale of 0.1 m are assumed. The latter parameter is used to simulate the second-by-second wind turbulence in accordance with the Frost-Long-Turner wind model [7]. The assumed high wind speed cutout control algorithm allows the wind turbine to restart only after 5 minutes have elapsed. This parameter is intended to avoid frequent high wind speed stops and starts. Based on past SNL VAWT analyses and test data, it is assumed that a single start operation consumes 1/500,000th of the machine's fatigue life and 1 kWh of energy from the electrical network.

Single High Wind Speed Cutout

The unique goal of ASYM development has been to aid in specifying high wind speed cutout algorithms. As shown in Equation (2), the figure of merit (FOM) is maximized if the machine life and energy capture are simultaneously maximized. Energy production can be maximized by operating the machine any time that the wind speed is above the cut-in level. However, the machine life may be drastically reduced by a fatigue failure if it is operated too often in high wind speeds. Therefore, the model is a useful tool to explore the concept of a high cutout wind speed that optimizes the FOM in Equation (2).

The fatigue results for a series of sample runs, with various high cutout wind speeds and wind-stress functions (i.e., curve slopes in Figure 1), are shown in Figure 4. Wind-stress functions of from 60 to 120 RMS psi/(m/s) were chosen to illustrate the results, although values below this range should be sought through proper structural design. The results, given in terms of expected machine life, indicate a very strong sensitivity of machine life to the wind-stress function. Conversely, the machine life is very sensitive to cutout wind speed over the range studied. For a wind-stress function of 120 RMS psi/(m/s), the expected machine life is, however, zero for all high wind speed cutout thresholds over the cutout wind speed range studied. In such a case, the VAWT design should be modified to reduce stresses.

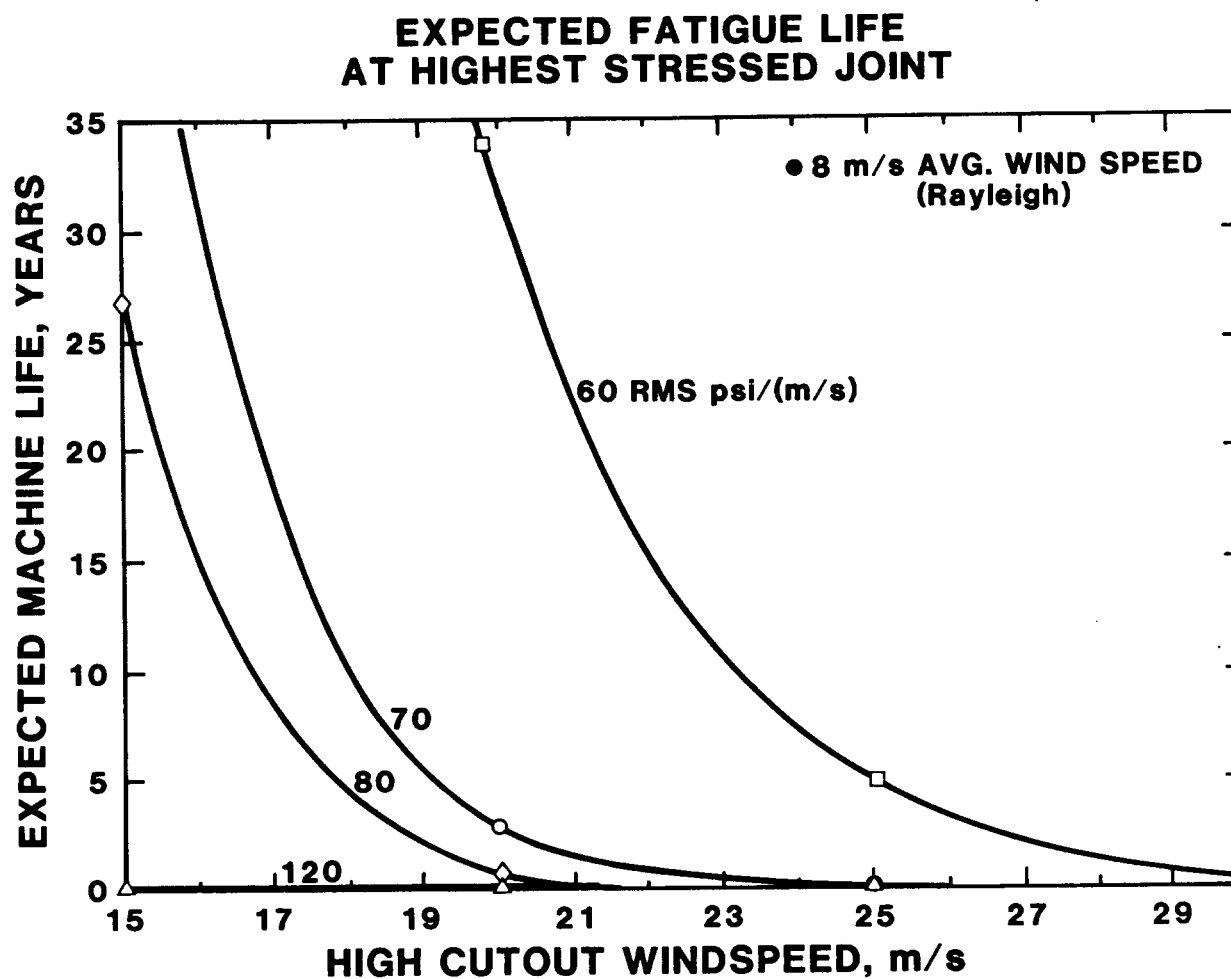


Figure 4. Expected Wind Turbine Life as a Function of the Cutout Wind Speed and the Wind-Stress Function at the Highest Stressed Rotor Joint

Energy capture will also vary with cutout wind speed threshold, but may have its greatest sensitivity over a different range of threshold values as shown by the damage and energy density curves in Figure 2. As an example, Figure 5 provides a plot of both the estimated percent energy capture and fatigue life for a VAWT that exhibits a wind-stress function of 60 RMS psi/(m/s) at the most highly stressed rotor joint. The shape of the two curves is indicative of the area under each curve in Figure 2 that exists to the left of a given cutout wind speed.

The FOM described in Equation (2) illustrates the multiplicative relationship between the two parameters plotted in Figure 5 and leads one to expect that an optimum cutout wind speed exists to maximize the FOM. Figure 6 is a plot of the variation in the FOM as a function of the cutout wind speed for the four values of wind-stress function considered in Figure 4. The results indicate that there is a clear optimum cutout wind speed in the vicinity of 20 m/s for a wind-stress function of 60 RMS psi/(m/s). However, for systems with a greater sensitivity between wind speed and vibratory stress, the following appears to be true;

- (1) All values of the FOM are expected to be lower for VAWTs with a wind-stress function higher than 60 RMS psi/(m/s), irrespective of cutout wind speed,
- (2) For mid-range wind-stress functions of 70 or 80 RMS psi/(m/s), the FOM will be maximized by reducing the machine cutout as low as possible over the range of interest,
- (3) For a 14 percent reduction in the wind-stress function in the vicinity of a 20-m/s cutout [i.e., from 70 to 60 RMS psi/(m/s)], the FOM can be increased nearly 400 percent,
- (4) For machines with very highly stressed joints [i.e., 120 RMS psi/(m/s)], it makes more economic sense to operate the machine as often as the wind allows to maximize the present value of the little energy that will be produced before a fatigue failure occurs, and
- (5) The values of the optimum cutout wind speed, or whether one exists at all, vary with the relative dominance of each term in Equation (2).

Therefore, it can be concluded that VAWT energy production, life, and economic benefits are extremely sensitive to the vibratory stress function at the most highly stressed machine components - generally found on the rotor. In VAWT design and engineering, 60 RMS psi/(m/s) should be considered a practical upper limit for the wind-stress function of an aluminum rotor joint. After that is achieved, it may make sense to select a cutout wind speed that maximizes the value of the energy produced over the life of the machine by using a design tool such as ASYM.

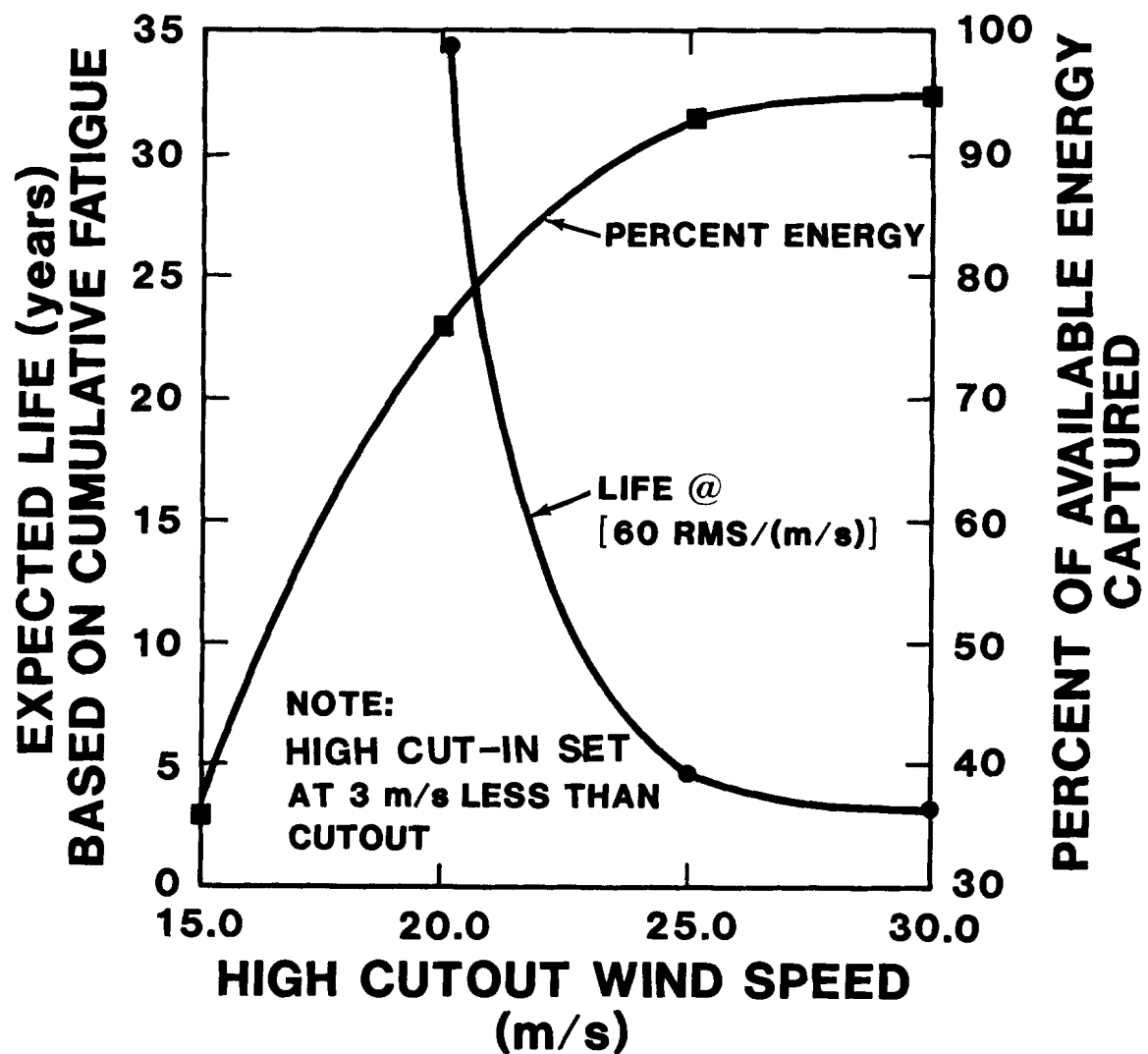


Figure 5. Variation in VAWT Expected Life and Energy Production with Cutout Wind Speed

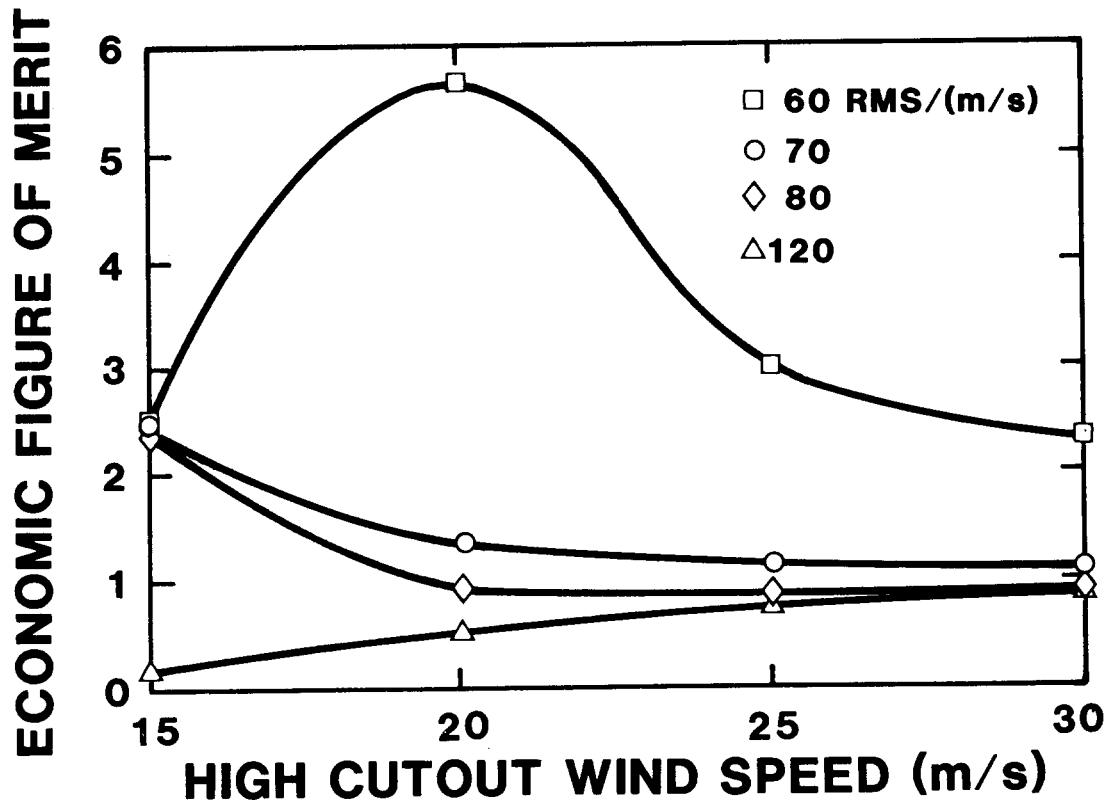


Figure 6. Variation in Economic Figure of Merit with Cutout Wind Speed for Various Values of Wind-Stress Function

Double High Wind Speed Cutout

A second high wind speed control approach employs a double moving wind speed average, as described above. This algorithm allows the wind turbine to shut down if the average wind speed exceeds a high wind speed threshold for a brief period, or if the average wind speed exceeds a lower wind speed value for a longer period. The period of time to satisfy the criterion is dictated by the width of a moving average wind speed window. In ASYM, this is specified by the number of sample points (at 2 seconds per sample) in the average. Generally the higher high speed criterion may be triggered when only one or two samples are above the threshold. On the other hand, the lower threshold may require as many as five or ten points in a moving average. Thus, average variability associated with a rising wind speed will generally trigger the lower wind speed cutout. However, if there is a sudden increase in wind speed due to a squall or a fast moving weather

front that may damage the machine, the higher threshold may be triggered before the lower average wind speed criterion is satisfied.

To study the merits of a double moving average cutout high wind speed, a series of ASYM runs was made in which the number of sample points in the lower cutout average (i.e., window width) were varied along with the lower high wind speed threshold. For the runs the following parameters were held constant:

- (1) Wind-stress function = 40 RMS psi/(m/s),
- (2) Higher high wind speed cutout threshold = 30 m/s, with two samples in the moving average window,
- (3) Wait time after cutout = 5 minutes, and
- (4) Surface roughness or turbulence length scale = 0.1 m.

Figure 7 is a plot of the number of stops per year as a function of the number of points in the lower high wind speed moving average window. The cutout wind speed threshold is a parameter that varies between 14 and 24 m/s.

It is clear that a low cutout wind speed produces a very large number of stops (and starts). For an 8-m/s site, at which a typical VAWT might operate approximately 3500 hours per year, an average of one stop per hour of operation might be expected for a low value of the cutout threshold. It is also clear from Figure 7 that the number of stops is very sensitive to the number of points in the moving average window width below four to six points per average (i.e., 8- to 12-second window width). As shown in Figure 8, the frequent stops give rise to a great deal of lost energy because the machine spends a substantial amount of time waiting to come back on line after each stop.

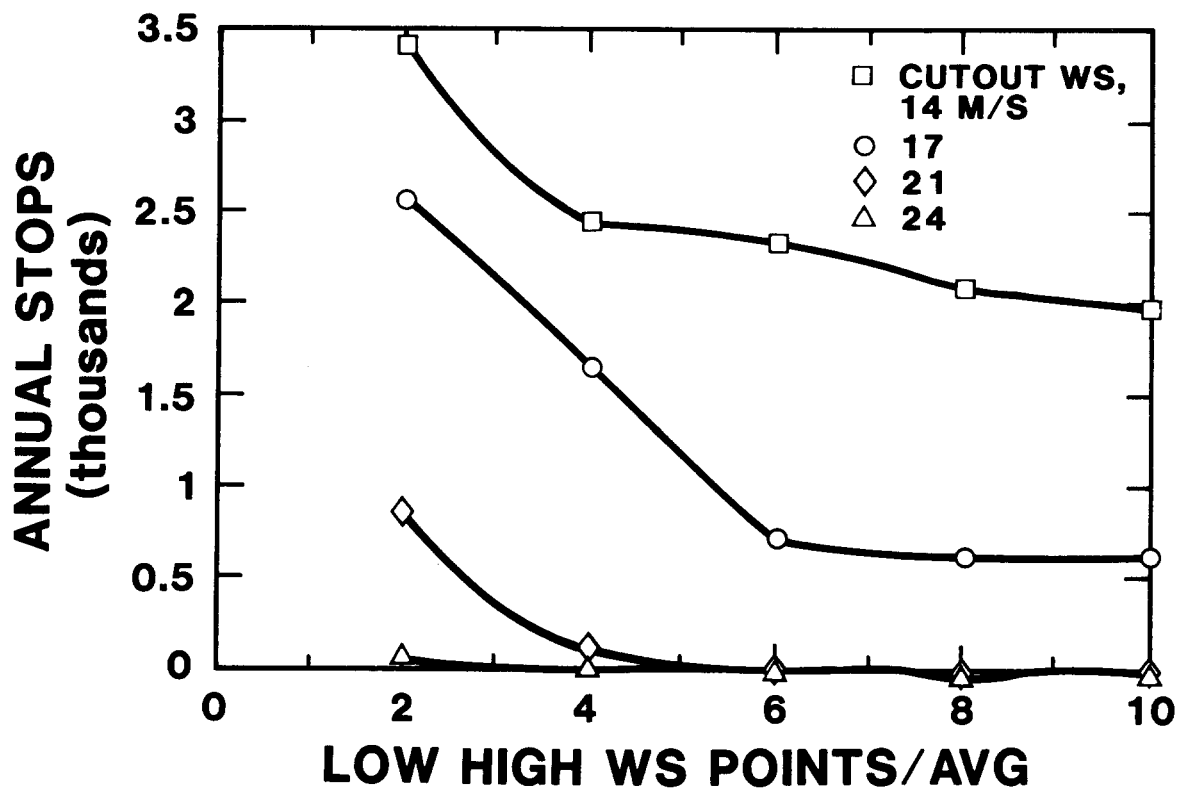


Figure 7. Estimated Number of Stops per Year Due to a Low High Wind Speed Cutout Algorithm

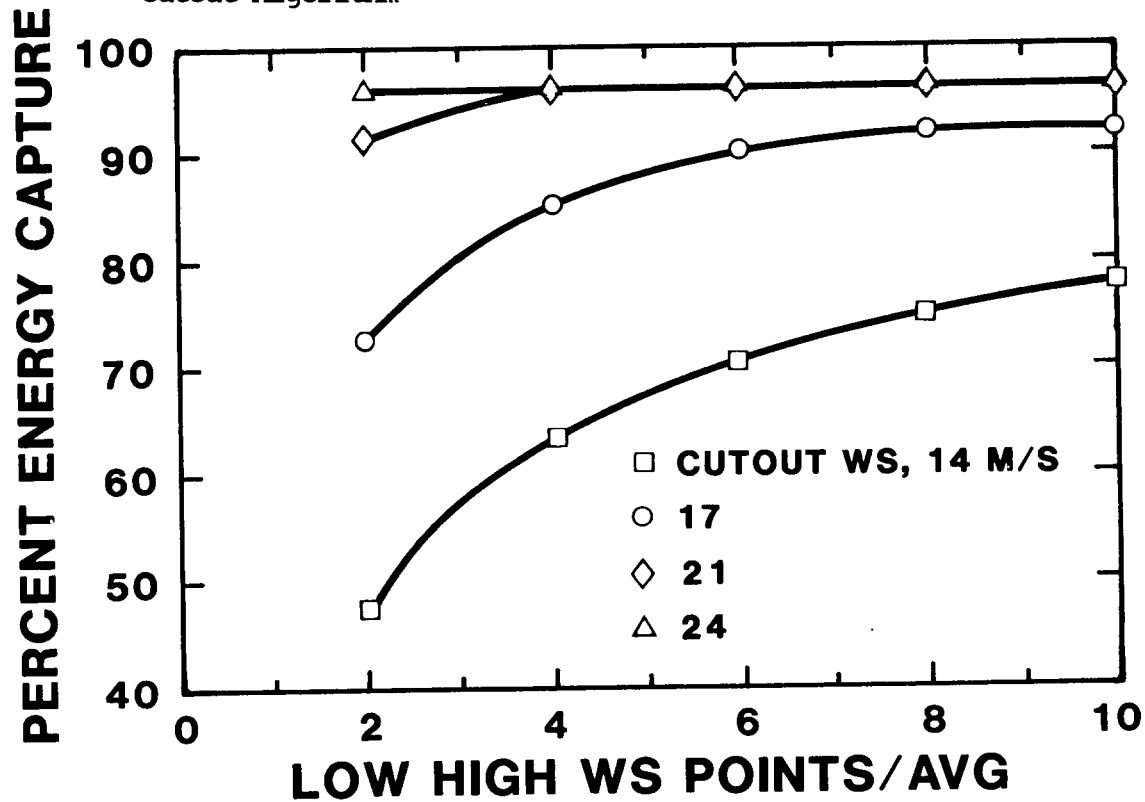


Figure 8. Variation in Estimated Energy Production as a Function of the Low High Wind Speed Moving Average Window Width and the Wind Speed Cutout Threshold

Although the cessation of operation in high wind speeds protects the machine from some fatigue damage, the overall effect of the frequent starts and stops alone can lead to an increase in fatigue damage. The overall effect of the control approach on the economics of the machine is summarized in the plot of FOM verses the number of points per average (i.e., window width) as shown in Figure 9. The results are consistent and in accordance with those shown in Figures 7 and 8.

As shown in Figure 7, a wider lower high wind speed moving average window width leads to fewer high wind speed stops. Also, a wider window leads to a better FOM as shown in Figure 9. Therefore, it can be concluded that a double average is not recommended for the conditions studied; only a single moving average appears to be prudent. A wind-stress function of 40 RMS psi/(m/s) was employed in this phase of the study. This value is in the range of those recommended for long-term machine operation with minimal fatigue. If the wind-stress function was substantially greater, as a result of an inadequate structural design approach, the use of a double moving average high cutout wind speed algorithm might be more appropriate as a means of protecting the machine from extreme damage.

Low Wind Coasting Algorithm

One low wind speed cut-in/cutout VAWT control approach that has been found to have merit is the "Canadian Coast" algorithm [4]. Some early Canadian VAWTs employed an over-running clutch on the high speed shaft that allowed the rotor to coast when rotating below normal operating speeds. The approach is appealing because it may reduce power consumption due to motoring in low wind conditions. Instead of turning the machine completely off when winds are insufficient to produce useful power, the machine is allowed to rotate freely, without generating power. If winds pick up again the rotor may speed up motored by the wind, or may be powered up to operating rpm more rapidly. In either case, less motoring power is required than if the machine were stopped.

The conditions under which the machine should be shut down during coasting operation can be easily sensed as follows:

- (1) If the wind speed is insufficient to allow the rotor speed to maintain a specific value,
- (2) If the allowed time in the coasting condition is exceeded, or
- (3) If a stress level at a specific location exceeds a prescribed threshold.

One risk in such a control approach is that the rotor rpm may dwell too often on a critical resonant frequency of the rotor or the drive train. With inadequate structural or aerodynamic damping, a short time in such a condition may lead to accelerated fatigue damage. For the simulation results to be discussed, the latter concern will not be addressed.

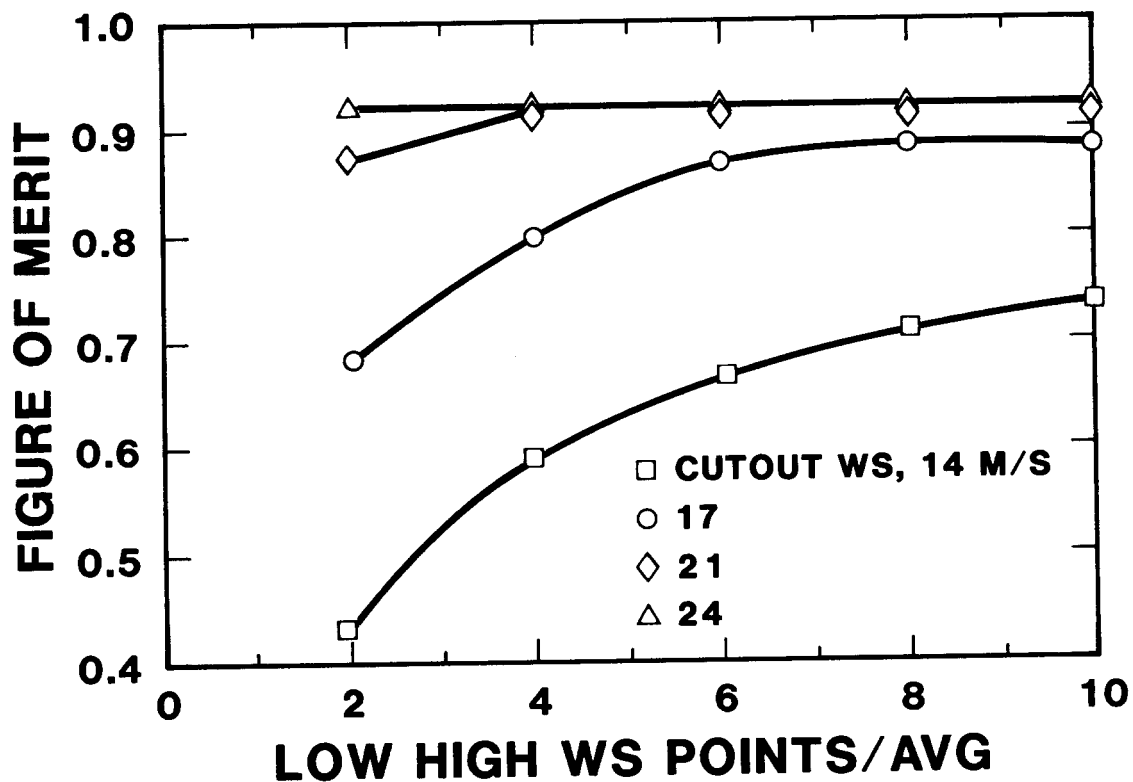


Figure 9. Economic Figure of Merit as a Function of the Lower High Wind Speed Moving Average Window Width and Cutout Threshold

ASYM was modified to simulate a specific low wind speed coasting algorithm. The main assumptions in the control algorithm were essentially the same as those employed in previous simulations, except that when the moving average wind speed falls below a cut-in speed the machine will go into the coasting mode. The amount of time permitted in the coasting mode was then varied to explore whether the control method reduced energy losses due to frequent starting and stopping. For the analyses discussed, rotor inertia is neglected.

Figure 10 is a plot of the results for an 8-m/s site. The figure provides a plot of start/stop energy losses as a function of permitted coasting time before a full shutdown is triggered. Site terrain roughness, which leads to wind turbulence according to Frost, Long, and Turner [7], is plotted as a parameter. The results lead to two important conclusions:

- (1) The magnitude of potential energy losses due to frequent VAWT starting and stopping is so small (less than 1 percent of energy produced) that it does not appear to be worth the risks of

produced) that it does not appear to be worth the risks of exciting mechanical resonances at different rotor speeds, and incurring associated accelerated fatigue damage. A careful design of the system structural dynamics may, however, permit such operation.

- (2) Improvements in start/stop energy losses are relatively insensitive to the turbulence level and the amount of coasting time permitted over the ranges studied. At very turbulent sites, sensitivities may be greater, but such sites are generally not preferred.

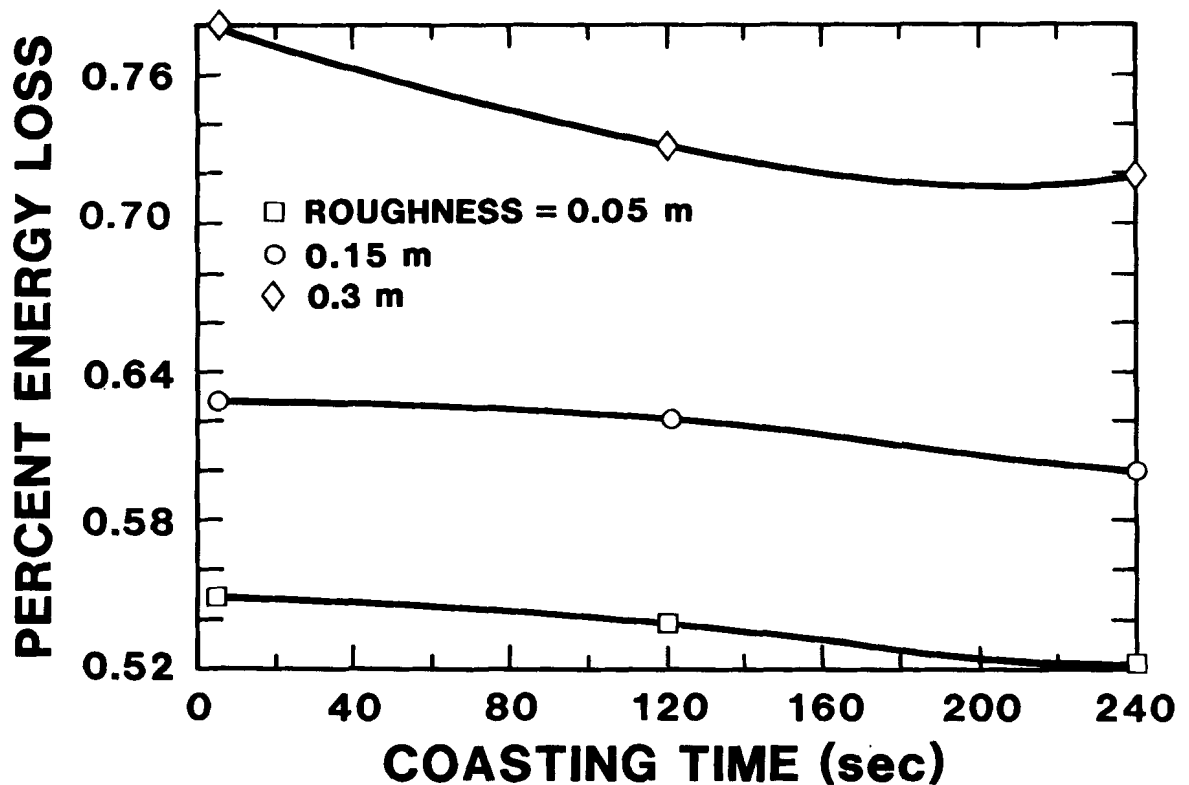


Figure 10. Calculated Low Wind Speed Start and Stop Energy Losses as a Function of Coasting Time and Terrain Roughness Length Scale

5. SUMMARY

The unavailability of abundant high-frequency wind data by which to study wind turbine control system performance, energy production, and fatigue damage has led to the development of a useful high-frequency random wind simulator. It has been applied to evaluate VAWT performance in the program ASYM. The preliminary results indicate the power and flexibility of the analytical tool. In general it can be concluded that VAWT fatigue life can be very sensitive to (1) the wind-stress function on the most highly stressed joint on the machine, and (2) the choice of parameters in the high wind speed cutout algorithm. ASYM permits the evaluation of an optimum cutout wind speed that maximizes project profit over the life of a machine. It was also found that a controller using a double moving high cutout wind speed average can lead to reduced economic benefits to the project if control parameters are inappropriately selected. Last, it was shown that start/stop energy losses are relatively small and the use of a low wind speed coasting algorithm produced marginal benefits in reducing energy losses. In general, ASYM has shown itself to be a useful design tool that can provide valuable guidance and insight in developing system control strategies.

6. REFERENCES

1. Miller, A. H., and W. J. Formica, "Long-Term Energy Capture and Effects of Optimizing Wind Turbine Operating Strategies," Proceedings of the Workshop on Large Horizontal-Axis Wind Turbines, Cleveland, Ohio, July 28-30, 1981, DOE Publication CONF-810752, pp. 337-351.
2. Veers, P. S., "Blade fatigue Life Assessment with Application to VAWTs," ASME J. of Solar Energy Engineering, V. 104, May 1982, pp. 106-111.
3. Veers, P. S., "A General Method of Fatigue Analysis of Vertical Axis Wind Turbine Blades," Sandia National Laboratories Report SAND82-2543, October 1983.
4. McNerney, G. M., "Control Algorithm Investigations," Proc. of the Vertical-Axis Wind Turbine (VAWT) Design Technology Seminar for Industry, April 1-3, 1980, Albuquerque, NM, Report SAND80-0984, August 1980.
5. McNerney, G. M., "Vertical Axis Wind Turbine Control Strategy," Sandia National Laboratories Report Number SAND81-1156, August 1981.
6. McNerney, G. M., and P. S. Veers, "A Markov Method of Simulating Non-Gaussian Wind Speed Time Series," Sandia National Laboratories Report SAND84-1227, January 1985.
7. Frost, W., Long, D. H., and R. E. Turner, "Engineering Handbook on the Atmospheric Environment Guidelines for Use in Wind Turbine Generator Development," NASA Technical Paper Number 1359, December 1979.
8. Miner, M. A., "Cumulative Damage in Fatigue," ASME J. of Applied Mechanics, 67:A159-A164, 1945.
9. Ashwill, T. D. and N. Slack, "Fatigue Life Prediction for Vertical Axis Wind Turbine Blades Using the LIFE Computer Program," Sandia National Laboratories Report, 1985.

DISTRIBUTION:

Alcoa Technical Center (5)
Aluminum Company of America
Alcoa Center, PA 15069
Attn: D. K. Ai
J. T. Huang
J. R. Jombock
M. Klingensmith
J. L. Prohaska

Alternative Sources of Energy
Milaca, MN 56353
Attn: L. Stoiaken

Amarillo College
Amarillo, TX 79100
Attn: E. Gilmore

American Wind Energy Association
1017 King Street
Alexandria, VA 22314

Arizona State University
University Library
Tempe, AZ 85281
Attn: M. E. Beecher

Dr. A. S. Barker
Trinity Western
7600 Glover Road
Langley, BC
CANADA V3A 4R9

Battelle-Pacific Northwest Laboratory
P.O. Box 999
Richland, WA 99352
Attn: L. Wendell

Bechtel Group, Inc.
P.O. Box 3965
San Francisco, CA 94119
Attn: B. Lessley

Dr. George Bergeles
Dept. of Mechanical Engineering
National Technical University
42, Patission Street
Athens, GREECE

Bonneville Power Administration
P.O. Box 3621
Portland, OR 97208
Attn: N. Butler

Burns & Roe, Inc.
800 Kinderkamack Road
Oradell, NJ 07649
Attn: G. A. Fontana

Canadian Standards Association
178 Rexdale Blvd.
Rexdale, Ontario, M9W 1R3
CANADA
Attn: T. Watson

Monique Carpentier
Energy, Mines and Resources
National Research Council
of Canada
Montreal Road
Ottawa, Ontario
CANADA K1A 0R6

Professor V. A. L. Chasteau
School of Engineering
University of Auckland
Private Bag
Auckland, NEW ZEALAND

Colorado State University
Dept. of Civil Engineering
Fort Collins, CO 80521
Attn: R. N. Meroney

Commonwealth Electric Co.
Box 368
Vineyard Haven, MA 02568
Attn: D. W. Dunham

Gale B. Curtis
Curtis Associates
3089 Oro Blanco Drive
Colorado Springs, CO 80917

M. M. Curvin
11169 Loop Road
Soddy Daisy, TN 37379

Department of Economic Planning
and Development
Barrett Building
Cheyenne, WY 82002
Attn: G. N. Monsson

Otto de Vries
National Aerospace Laboratory
Anthony Fokkerweg 2
Amsterdam 1017
THE NETHERLANDS

DOE/ALO
Albuquerque, NM 87115
Attn: G. P. Tennyson

DOE/ALO
Energy Technology Liaison Office
NGD
Albuquerque, NM 87115
Attn: Capt. J. L. Hanson, USAF

DOE Headquarters (20)
Wind/Oceans Technologies Division
1000 Independence Avenue
Washington, DC 20585
Attn: L. J. Rogers
P. R. Goldman

J. B. Dragt
Nederlands Energy Research Foundation
(E.C.N.)
Physics Department
Westerduinweg 3 Petten (nh)
THE NETHERLANDS

Dynergy Systems Corporation
821 West L Street
Los Banos, CA 93635
Attn: C. Fagundes

Electric Power Research Institute
3412 Hillview Avenue
Palo Alto, CA 94304
Attn: E. Demeo
F. Goodman

Dr. Norman E. Farb
10705 Providence Drive
Villa Park, CA 92667

Alcir de Faro Orlando
Pontificia Universidade Catolica-PUC/RJ
Mechanical Engineering Department
R. Marques de S. Vicente 225
Rio de Janeiro, BRAZIL

FloWind Corporation (2)
1183 Quarry Lane
Pleasanton, CA 94566
Attn: L. Schienbein
B. Im

A. D. Garrad
Garrad Hasson
10 Northampton Square
London EC1M 5PA
UNITED KINGDOM

Gates Learjet
Mid-Continent Airport
P.O. Box 7707
Wichita, KS 67277
Attn: G. D. Park

H. Gerardin
Mechanical Engineering Department
Faculty of Sciences and Engineering
Universite Laval-Quebec, G1K 7P4
CANADA

R. T. Griffiths
University College of Swansea
Dept. of Mechanical Engineering
Singleton Park
Swansea, SA2 8PP
UNITED KINGDOM

Helion, Inc.
Box 445
Brownsville, CA 95919
Attn: J. Park, President

Indal Technologies, Inc. (2)
3570 Hawkestone Road
Mississauga, Ontario
CANADA L5C 2V8
Attn: D. Malcolm
C. Wood

Institut de Recherche d'Hydro-Quebec
1800, Montee Ste-Julie
Varennnes, Quebec, JOL 2P.O.
CANADA
Attn: Bernard Masse

Iowa State University
Agricultural Engineering, Room 213
Ames, IA 50010
Attn: L. H. Soderholm.

K. Jackson
West Wind Industries
P.O. Box 1705
Davis, CA 95617

M. Jackson
McAllester Financial
1816 Summit
W. Lafayette, IN 47906

Kaiser Aluminum and Chemical
Sales, Inc.
14200 Cottage Grove Avenue
Dolton, IL 60419
Attn: A. A. Hagman

Kaiser Aluminum and Chemical
Sales, Inc.
6177 Sunol Blvd.
P.O. Box 877
Pleasanton, CA 94566
Attn: D. D. Doerr

Kansas State University
Electrical Engineering Department
Manhattan, KS 66506
Attn: Dr. G. L. Johnson

R. E. Kelland
The College of Trades and Technology
P.O. Box 1693
Prince Philip Drive
St. John's, Newfoundland, A1C 5P7
CANADA

KW Control Systems, Inc.
RD#4, Box 914C
South Plank Road
Middletown, NY 10940
Attn: R. H. Klein

Kalman Nagy Lehoczky
Cort Adelers GT. 30
Oslo 2, NORWAY

L. K. Liljergren
1260 S.E. Walnut #5
Tustin, CA 92680

L. Liljidahl
Building 005, Room 304
Barc-West
Beltsville, MD 20705

Olle Ljungstrom
FFA, The Aeronautical Research
Institute
Box 11021
S-16111 Bromma, SWEDEN

Robert Lynette
R. Lynette & Assoc., Inc.
15042 NE 40th Street
Suite 206
Redmond, WA 98052

Massachusetts Institute of Technology
77 Massachusetts Avenue
Cambridge, MA 02139
Attn: Professor N. D. Ham
W. L. Harris, Aero/Astro Dept.

H. S. Matsuda
Composite Materials Laboratory
Pioneering R&D Laboratories
Toray Industries, Inc.
Sonoyama, Otsu, Shiga, JAPAN 520

G. M. McNerney
US Wind Power
160 Wheeler Road
Burlington, MA 01803

Michigan State University
Division of Engineering Research
East Lansing, MI 48825
Attn: O. Krauss

Napier College of Commerce and
Technology
Tutor Librarian, Technology Faculty
Colinton Road
Edinburgh, EH10 5DT
ENGLAND

National Rural Electric
Cooperative Assn
1800 Massachusetts Avenue, NW
Washington, DC 20036
Attn: Wilson Prichett, III

Natural Power, Inc.
New Boston, NH 03070
Attn: Leander Nichols

Northwestern University
Dept. of Civil Engineering
Evanston, IL 60201
Attn: R. A. Parmalee

Ohio State University
Aeronautical and Astronautical Dept.
2070 Neil Avenue
Columbus, OH 43210
Attn: Professor G. Gregorek

Oklahoma State University
Mechanical Engineering Dept.
Stillwater, OK 76074
Attn: D. K. McLaughlin

Oregon State University
Mechanical Engineering Dept.
Corvallis, OR 97331
Attn: R. E. Wilson

Pacific Gas & Electric Co.
3400 Crow Canyon Road
San Ramon, CA 94583
Attn: T. Hillesland

Ion Paraschivoiu
Department of Mechanical Engineering
Ecole Polytechnique
CP 6079
Succursale A
Montreal H3C 3A7
CANADA

Jacques Plante
Hydro Quebec
Place Dupuis Ile etage
855 est rue Ste-Catherine
Montreal, Quebec
CANADA H2L 4P5

The Power Company, Inc.
P.O. Box 221
Genesee Depot, WI 53217
Attn: A. A. Nedd

Power Technologies, Inc.
P.O. Box 1058
Schenectady, NY 12301-1058
Attn: Eric N. Hinrichsen

Public Service Co. of New Hampshire
1000 Elm Street
Manchester, NH 03105
Attn: D. L. C. Frederick

Public Service Company of New Mexico
P.O. Box 2267
Albuquerque, NM 87103
Attn: M. Lechner

RANN, Inc.
260 Sheridan Ave., Suite 414
Palo Alto, CA 94306
Attn: A. J. Eggers, Jr.

Dr. R. Ganesh Rajagopalan, Asst. Prof.
Aerospace Engineering Department
Iowa State University
404 Town Engineering Bldg.
Ames, IA 50011

The Resources Agency
Department of Water Resources
Energy Division
P.O. Box 388
Sacramento, CA 95802
Attn: R. G. Ferreira

Reynolds Metals Company
Mill Products Division
6601 West Broad Street
Richmond, VA 23261
Attn: G. E. Lennox

R. G. Richards
Atlantic Wind Test Site
P.O. Box 189
Tignish P.E.I., COB 2B0
CANADA

Riso National Laboratory
Postbox 49
DK-4000 Roskilde
DENMARK
Attn: Troels Friis Pedersen
Helge Petersen

A. Robb
Memorial University of Newfoundland
Faculty of Engineering and Applied
Sciences
St. John's Newfoundland, A1C 5S7
CANADA

Dr. Ing. Hans Ruscheweyh
Institut für Leichtbau
Technische Hochschule Aachen
Wullnerstrasse 7
FEDERAL REPUBLIC OF GERMANY

Beatrice de Saint Louvent
Etablissement d'Etudes et de
Recherches
Météorologiques
77 Rue de Serves
92106 Boulogne-Billancourt Cedex
FRANCE

Gwen Schreiner
Librarian
National Atomic Museum
Albuquerque, NM 87185

Arnan Seginer
Professor of Aerodynamics
Technion-Israel Institute of Technology
Department of Aeronautical Engineering
Haifa
ISRAEL

Mr. Farrell Smith Sellar, Editor
Wind Energy News Service
P.O. Box 4008
St. Johnsbury, VT 05819

David Sharpe
Dept. of Aeronautical Engineering
Queen Mary College
Mile End Road
London, E1 4NS
UNITED KINGDOM

Kent Smith
Instituto Tecnológico Costa Rica
Apartado 159 Cartago
COSTA RICA

Solar Energy Research Institute
1617 Cole Boulevard
Golden, CO 80401
Attn: R. W. Thresher

Bent Sorenson
Roskilde University Center
Energy Group, Bldg. 17.2
IMFUFA
P.O. Box 260
DK-400 Roskilde
DENMARK

Peter South
ADECON
32 Rivalda Road
Weston, Ontario, M9M 2M3
CANADA

Southern California Edison
Research & Development Dept., Room 497
P.O. Box 800
Rosemead, CA 91770
Attn: R. L. Scheffler

G. Stacey
The University of Reading
Department of Engineering
Whiteknights, Reading, RG6 2AY
ENGLAND

Stanford University
Dept. of Aeronautics and
Astronautics Mechanical Engineering
Stanford, CA 94305
Attn: Holt Ashley

Dr. Derek Taylor
Alternative Energy Group
Walton Hall
Open University
Milton Keynes, MK7 6AA
UNITED KINGDOM

R. J. Templin (3)
Low Speed Aerodynamics Laboratory
NRC-National Aeronautical Establishment
Montreal Road
Ottawa, Ontario, K1A 0R6
CANADA

Texas Tech University (2)
Mechanical Engineering Dept.
P.O. Box 4289
Lubbock, TX 79409
Attn: J. W. Oler

K. J. Touryan
Moriah Research
6200 Plateau Dr.
Englewood, CO 80111

Tulane University
Dept. of Mechanical Engineering
New Orleans, LA 70018
Attn: R. G. Watts

Tumac Industries, Inc.
650 Ford Street
Colorado Springs, CO 80915
Attn: J. R. McConnell

J. M. Turner
Terrestrial Energy Technology
Program Office
Energy Conversion Branch
Aerospace Power Division/
Aero Propulsion Lab
Air Force Systems Command (AFSC)
Wright-Patterson AFB, OH 45433

United Engineers and Constructors, Inc.
P.O. Box 8223
Philadelphia, PA 19101
Attn: A. J. Karalis

Universal Data Systems
5000 Bradford Drive
Huntsville, AL 35805
Attn: C. W. Dodd

University of California
Institute of Geophysics
and Planetary Physics
Riverside, CA 92521
Attn: Dr. P. J. Baum

University of Colorado
Dept. of Aerospace Engineering Sciences
Boulder, CO 80309
Attn: J. D. Fock, Jr.

University of Massachusetts
Mechanical and Aerospace
Engineering Dept.
Amherst, MA 01003
Attn: Dr. D. E. Cromack

University of New Mexico
New Mexico Engineering
Research Institute
Campus P.O. Box 25
Albuquerque, NM 87131
Attn: G. G. Leigh

University of Oklahoma
Aero Engineering Department
Norman, OK 73069
Attn: K. Bergey

University of Sherbrooke
Faculty of Applied Science
Sherbrooke, Quebec, J1K 2R1
CANADA
Attn: A. Laneville
P. Vittecoq

The University of Tennessee
Dept. of Electrical Engineering
Knoxville, TN 37916
Attn: T. W. Reddoch

USDA, Agricultural Research Service
Southwest Great Plains Research Center
Bushland, TX 79012
Attn: Dr. R. N. Clark

Utah Power and Light Co.
51 East Main Street
P.O. Box 277
American Fork, UT 84003
Attn: K. R. Rasmussen

W. A. Vachon (25)
W. A. Vachon & Associates
P.O. Box 149
Manchester, MA 01944

Dirk Vandenberghe
State Univ. of Ghent
St. Pietersnieuwstraat 41
9000 Ghent
BELGIUM

Washington and Lee University
P.O. Box 735
Lexington, VA 24450
Attn: Dr. R. E. Akins

Washington State University
Dept. of Electrical Engineering
Pullman, WA 99163
Attn: F. K. Bechtel

West Texas State University
Government Depository Library
Number 613
Canyon, TX 79015

West Texas State University
Department of Physics
P.O. Box 248
Canyon, TX 79016
Attn: V. Nelson

West Virginia University
Dept. of Aero Engineering
1062 Kountz Avenue
Morgantown, WV 26505
Attn: R. Walters

D. Westlind
Central Lincoln People's Utility
District
2129 North Coast Highway
Newport, OR 97365-1795

Wichita State University
Aero Engineering Department (2)
Wichita, KS 67208
Attn: M. Snyder
W. Wentz

Wind Power Digest
P.O. Box 700
Bascom, OH 44809
Attn: Michael Evans

Wisconsin Division of State Energy
8th Floor
101 South Webster Street
Madison, WI 53702
Attn: Wind Program Manager

1520	C. W. Peterson
1522	R. C. Reuter, Jr.
1523	J. H. Biffle
1524	A. K. Miller
1524	D. W. Lobitz
1550	R. C. Maydew
1552	J. H. Strickland
1556	G. F. Homicz
2525	R. P. Clark
3141-1	C. L. Ward (5)
3151	W. L. Garner (3)
3154-3	C. H. Dalin (28)
	For DOE/OSTI (Unlimited Release)
3160	J. E. Mitchell (15)
3161	P. S. Wilson
6000	D. L. Hartley
6200	V. L. Dugan
6220	D. G. Schueler
6225	H. M. Dodd (50)
6225	T. D. Ashwill
6225	D. E. Berg
6225	T. C. Bryant
6225	L. R. Gallo
6225	P. C. Klimas
6225	S. D. Nicolaysen
6225	D. S. Oscar
6225	M. E. Ralph
6225	D. C. Reda
6225	M. A. Rumsey
6225	L. L. Schluter
6225	W. A. Stephenson
6225	H. J. Sutherland
7111	J. W. Reed
7544	D. R. Schafer
7544	T. G. Carne
7544	J. Lauffer
8024	P. W. Dean
9100	R. G. Clem
9122	T. M. Leonard